

Quantum gravity in the sky

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Abstract

Quantum gravity is known to be mostly a kind of metaphysical speculation. In this brief essay, we try to argue that, although still extremely difficult to reach, observational signatures can in fact be expected. The early universe is an invaluable laboratory to probe "Planck scale physics". With the example of Loop Quantum Gravity, we detail some expected features.

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Building a quantum theory of gravity –that is a quantum model of spacetime itself– is often considered as the most outstanding problem of contemporary physics. Why ? Because this is the unavoidable horizon for unification, explain most scientists. This might not be that clear. Unquestionably, unification has been an efficient guide for centuries: it worked with Kepler, with Maxwell, with Glashow, Salam and Weinberg. Yet, is the World more "unified" today than at the end of the nineteenth century ? Let us consider the macrocosm : stars, planets, comets, dust, cosmic-rays, pulsars, quasars, white dwarfs, black holes, magnetohydrodynamics turbulence, galaxy collisions... Is this a "unified" firmament ? Naturally, one should better consider the microcosm. However, there are today about 120 degrees of freedom in the standard model (not even mentioning supersymmetry), which is slightly *more* than the number of atoms in the old Mendeleev periodic table. Of course, it might be more relevant to consider interactions instead of matter constituents. But, once again, grand unification is still missing and, to account for the accelerated expansion of the universe, many of us rely on a quintessence scenario¹. Quintessence means *quintus essentia*, that is "fifth force". We

¹This is obviously not the only possibility. A true cosmological constant, as advocated in [1], is even possible although the numerical value doesn't fit quantum mechanical expectations.

will not elaborate here on the string theory landscape [2] which, interestingly, exhibits an unprecedented diversity within the realm of a tentative fully unified model². The roads toward unification are probably much more intricate than usually thought: they might very well be organized as a kind of *rhizome*³.

Does this mean that the idea of quantum gravity itself should be forgotten? After all, this has been shown to be such an incredibly difficult theory to establish that the wise attitude could just be to withdraw from this apparently never-ending quest. Unfortunately, it is impossible to ignore the "gravity-quantum" tension⁴. The first reason is that the quantum world interacts with the gravitational field. This, in itself, requires gravity to be understood in a quantum paradigm, as can be demonstrated by appropriate thought experiments [7]. The second reason is that, the other way round, gravity requires quantum field theories to live in curved spaces. Just because of the equivalence principle, it is easy to get convinced [8] that this cannot be rigorously implemented without quantum general relativity. Basically speaking, the nonlinearity of gravity frustrates all attempts to ignore quantum gravity: each time a strong gravitational field is involved the coupling to gravitons should also be strong. The third reason is the existence of singularities: general relativity predicts, by itself, its own breakdown (as exhibited, *e.g.*, by the Penrose-Hawking theorems [9]). This is a truly remarkable feature. Although the first two reasons can, to some extent, be considered as "heuristic" motivations, the last one does imperatively require a way out. Pure general relativity ontologically fails.

It is sometimes said either that we have too many candidate theories [10] for quantum gravity or that we don't have a single (convincing) one [11]. Although apparently contradictory, both statements are in fact correct. This is a quite specific situation: many different approaches are investigated, all are promising, but none is fully consistent. At this stage, experiments are obviously missing to eradicate those theories that are deeply on the wrong track and to improve those that might be correct. Unfortunately, quantum gravity is known to be out of reach of any possible experiment⁵. We shall now underline that this might not be true.

As previously stated, singularities are the "places" where the departure of quantum gravity from standard predictions is expected to be the largest (namely infinite). Curing singular pathologies is indeed the first *requisit* for any tentative theory of quantum gravity. This qualifies black holes and the Big Bang neighborhood as ideal places for quantum gravity investigations. From now on, we focus on Loop Quantum Gravity (LQG) as a prototype model for a background-independent and non-perturbative quantization of general relativity [11, 12]. Clear predictions can be made for the spectrum of black holes [13], leading to specific signatures in their Hawking evaporation products [14]. Although tantalizing, this approach⁶ is unfortunately not very promising as no

²For a more philosophical investigation of diversity and unification in physics, one can consider [3].

³We refer here to the philosophical concept of the "image of thought", as suggested, within the so-called *French Theory*, in [4].

⁴A possible way out might still be conceivable in the framework of "emergent" or "entropic" gravity [5, 6].

⁵The ratio of the Planck scale to the LHC scale is roughly the same than the ratio of the human scale to the distance to the closest star.

⁶A very interesting alternative to probe quantum gravity would be to search for a violation of the

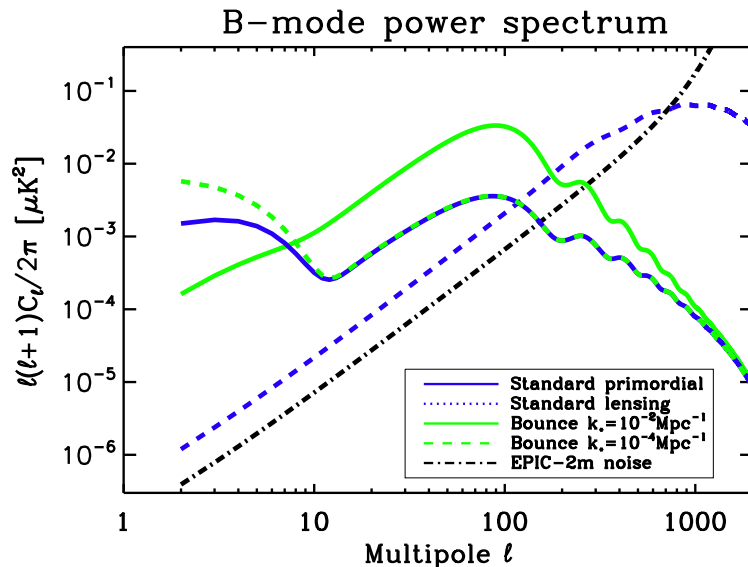


Figure 1: B-mode power spectrum in the "standard model" and with a LQC-induced bounce. The lensing background and the sensitivity of an Epic-like experiment are also displayed to underline the detectability.

light black hole has been detected so far [15] (unless large extra-dimensions are assumed, producing small black holes is extremely difficult and would typically require a density contrast in the early universe 10^4 times larger than measured). We are left with cosmology and the Big Bang singularity resolution. This is precisely the key prediction of LQG as applied to the universe as a whole – the so-called Loop Quantum Cosmology (LQC) model [18]: the Big Bang is replaced by a Big Bounce.

Fortunately, it is now becoming clear that Loop Quantum Cosmology (LQC) provides much more than an elegant smoothing of the primordial singularity. It somehow *predicts* inflation. We will resist the temptation to compute the accurate probability for inflation to occur in this model [19], as it highly depends on the chosen measure and, *a fortiori*, to compute the probability for the Universe to be compatible with WMAP data [20]: there are contingent phenomena in the Universe and, as long as data are added or refined, the probability will inevitably decrease, even if the theory is correct. The fact remains that [21], even for the simplest model, without any fine-tuning (say for a universe filled with a massive scalar field), the usual "friction" term of the Klein Gordon equation ($\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$) becomes an anti-friction one in the contracting phase of the universe, therefore obliging the field to climb up its potential⁷ ! Just after the bounce, the Universe begins to expand, the Hubble parameter becomes positive and

Lorentz invariance using photons emitted, *e.g.*, by a gamma-ray burst [16]. This is extremely motivating but not conclusive as LQG -among others- do *not* predict any clear violation of the Lorentz invariance [17].

⁷In our opinion, establishing that this result remains true when anisotropies –that are growing faster than anything else in the contracting phase– are taken into account is the major challenge of this model for the forthcoming years (some preliminary encouraging results are already available [22]).

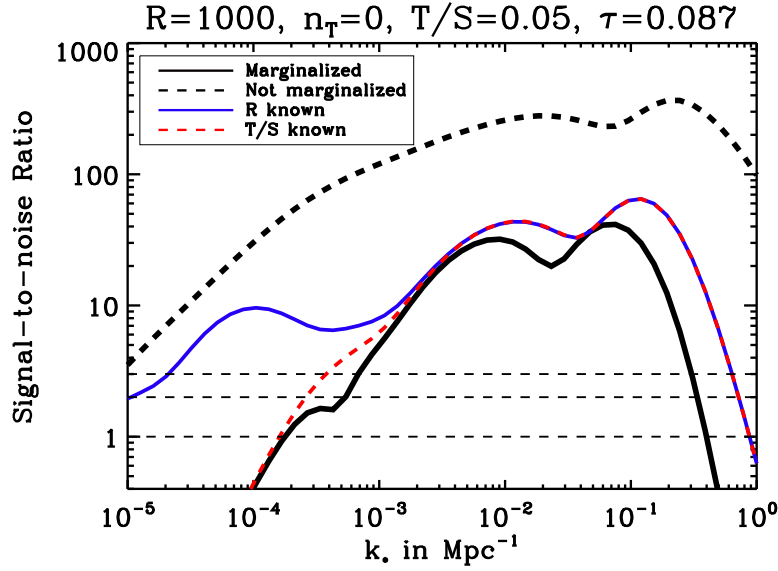


Figure 2: Signal-to-noise ratio for the detection of a LQC bounce as a function of the k_* parameter, which determines the transition between the suppressed spectrum and the standard spectrum, for different marginalization schemes.

therefore acts as friction: the field is nearly frozen and standard "slow-roll" inflation takes place. This is a good point: the canonical quantization of general relativity "à la loop" makes inflation much more natural than in the standard cosmological framework (see [23] for some "naturalness" problems of the inflationary paradigm). This is however not enough to qualify cosmology as a probe for (loop) quantum gravity.

The situation dramatically changes when one investigates a bit more into the details the propagation of perturbations through the bounce⁸. It is often argued that inflation erases all possible footprints of quantum gravity due to the huge increase of the scale factor. This is not entirely true. The deep reason for this is the following: in a "Fock space" language, the occupation numbers *after* inflation are sensitive to the occupation numbers *before* inflation, just because the quantity which is amplified is the number of particles per unit cell of phase space, whose volume $d^3x d^3k / (2\pi)^3$ is unaffected by the huge increase of the scale factor (whereas $d^3x \propto a^3$).

The basic equation to be solved to investigate gravity waves is the following⁹:

$$\frac{d^2}{d\eta^2} h_a^i + 2\mathcal{H} \frac{d}{d\eta} h_a^i - \nabla^2 h_a^i + m_Q^2 h_a^i = 0, \quad (1)$$

where h_a^i are gravitational perturbations, η and \mathcal{H} are the conformal time and Hubble

⁸Perturbation theory and averaging cosmology are deeply interconnected. The key point is that statistical properties can now be accurately computed.

⁹For the sake of simplicity we have here just considered the so-called "holonomy" correction. The other main LQC term, the inverse triad correction, does not change the qualitative analysis presented in this note.

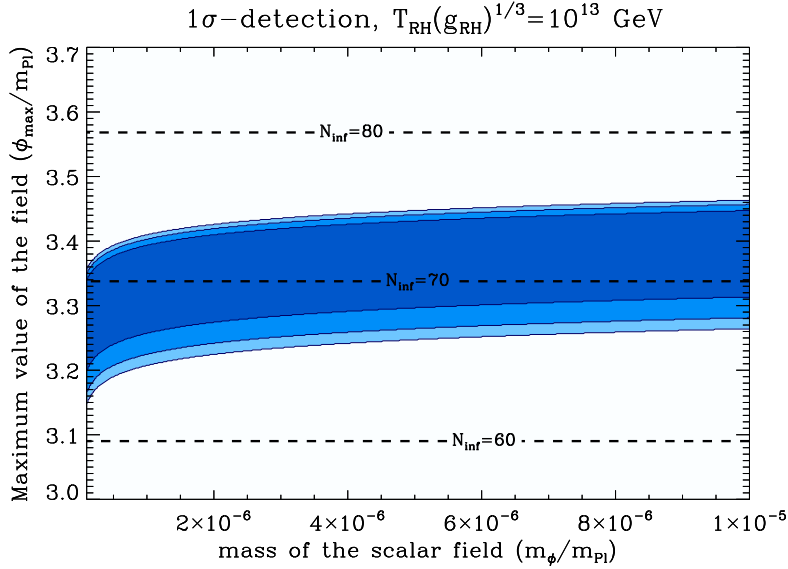


Figure 3: Detectability (1σ , 2σ and 3σ) as a function of the mass of the field and of the maximum energy reached just after the bounce.

constant. The effective mass term, which encodes LQC corrections, is given by

$$m_Q^2 := 16\pi G a^2 \frac{\rho}{\rho_c} \left(\frac{2}{3}\rho - V \right), \quad (2)$$

with $\rho_c \approx \rho_{Pl}$, whereas the background follows:

$$H^2 = \frac{\kappa}{3}\rho \left(1 - \frac{\rho}{\rho_c} \right). \quad (3)$$

The numerical resolution leads to a power spectrum which is quadratically suppressed below some scale k_* , exhibits a bump of amplitude R around k_* , and then follows, in the ultra-violet limit, the (nearly) scale-invariant behavior. This can be easily understood: large physical scales ($k < k_*$) crossed the horizon only once and were frozen in the Minkowski vacuum ($P(k) \propto k^2$), whereas small scales ($k > k_*$) followed a nearly standard history (they exited the horizon during inflation and re-entered later). This deformed primordial power spectrum can be used as an input to estimate the resulting B-mode Cosmic Microwave Background (CMB) spectrum (Fig. 1). It exhibits some deviations with respect to the usual picture that could be probed by the next-generation cosmology experiments (either Planck or, in the long run, with a polarization-dedicated experiment). Using this spectra and taking into account both the instrumental noise and the astrophysical noise, we have estimated with a Fisher analysis, as shown in Fig. 2, the signal-to-noise ratio as a function of the k_* scale. Furthermore, those parameters can be translated into more fundamental ones, as exhibited on Fig. 3: the value of the field at the beginning of inflation (or, alternatively, the fraction of potential energy at the bounce) and its mass. Obviously, a window is opened for detection (see [24] for details on the material used to build this picture).

Of course, this approach is far from being perfect or fully convincing. The parameter space that can be probed remains quite limited, the backreaction effects are still neglected, and, most importantly, the temperature CMB spectrum –which is already observed– has not yet been fully computed (see [25] for recent progress). Not to mention that the algebra of constraints for tensor modes should be non-trivially modified due to the consistency of Poisson brackets derived for scalar modes. The signature might even change and become euclidean near the bounce. However, with the example of LQG, it seems that quantum gravity, which has long been thought to be "untestable", might become an observational science¹⁰. String theory has also interesting predictions for the CMB, *e.g.* in the Ekpyrotic scenario [28], in string gas cosmology [29], or in pre Big Bang cosmology [30], to cite only a few models. In the sky, quantum gravity could be confronted with predictions! Astronomy has already been extraordinarily useful to discover new phenomena. Even with planets alone: while anomalies in the orbit of Uranus led to the discovery of Neptune, anomalies in the orbit of Mercury required the discovery of general relativity. Either by adding new constituents or by changing the laws of physics, explaining data from the sky remains one of the greatest challenges and best insight toward "new physics".

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¹⁰This is, of course, not the only way to test this kind of models thanks to the CMB: non-gaussianities (see, *e.g.*, [26] for a review) or low-variance circles [27] are other possible probes.

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